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JSC THUNDERSTORM EXPERIMENT RESULTS

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LYNDON B. JOHNSON SPACE CENTER

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1.0 INTRODUCTION

The Florida peninsula experiences the greatest number and some of the most electrically severe thunderstorms of any area within the continental United States. Thus, the location of the Space Shuttle launch and landing site in this area presents unique weather-related problems, particularly for summertime vehicle operations. To gain more insight into the various effects of lightning and thunderstorms on future Shuttle vehicle operations in that area, the Lyndon B. Johnson Space Center conducted an experiment during the summer of 1976 to obtain data on the nature of electric fields in the vicinity of thunderstorms and particularly in the region of cumulonimbus cloud anvils during their various stages of build-up, maturity, and dissipation. These data supplemented the airborne electric field data collected during the summer of 1975 in support of the Apollo Soyuz Test Project and the Viking launches.

A Learjet aircraft was outfitted with four special electric field meters for collecting data. The onboard aircraft radar was also used to investigate cells embedded in large thunderstorm systems such as those found in frontal and squall line activities. Data were collected from 33 storm cells and will be used primarily to establish a launch criteria to preclude triggering lightning during Shuttle vehicle operations in close proximity to thunderstorms. This report presents some of the more pertinent data and findings.

2.0 OBJECTIVE

The objective was to collect electric field data to answer the following questions:

a. Are the electric fields in the vicinity of thunderstorms, and in particular, those near anvil clouds such that lightning can be triggered by the Shuttle vehicle during launch, or by the Orbiter during landing?

b. If so, what characteristics identify the clouds that would most likely produce triggered lightning?

3.0 EXPERIMENT CONFIGURATION AND CALIBRATION

The experiment equipment consisted of a Learjet aircraft equipped with an airborne-electric-field-measurement system. In addition, a portable cassette tape recorder and a handheld 35-mm camera were used to document experiment conditions.

The Learjet Model 24B was furnished by Ames Research Center. The airborne electric field meter system, consisting of system electronics, data recorders, and four sensors, was furnished by Stanford Research Institute. The system

electronics and data recorders were installed in the aircraft cabin and received their power from two solid-state inverters mounted in the aircraft baggage section. The sensors were flush mounted with the aircraft external surface at locations shown in figure 1. The surface adjacent to each sensor was painted to prevent static electrical charge accumulation during flight.

The airborne-electric-field-measurement system measured the intensity of electric fields at various altitudes in the vicinity of thunderstorms. The system (fig. 2) consisted of the field-mill sensors (fig. 3), a series of amplifiers, an analog processor, and a data recording device.

Three field-mill sensors were installed so that the ambient field components (E_x, E_y, and E_z) could be located in the coordinate system formed along the aircraft flight path with the aircraft as the origin of the system. Figure 1 presents the orientation of the field mills. The fourth field mill measured the potential (V_a) of the aircraft.

Three amplifiers, each with an amplification factor of 5, were in the circuit between each field mill sensor and the analog processor, thus providing four possible gains that could be switched in or out of the system so that maximum readings would not exceed the recorder capability and the analog processor would not be saturated when high fields were sensed. The analog processor included a summing amplifier that converted the direct field-mill sensed values into raw electric-field components.

The field mills were calibrated prior to every flight. Figure 4 shows the configuration of the calibration equipment. It consisted of an aluminum plate that was placed 10 centimeters in front and parallel to the face of the field mill. The aluminum plate was connected to a power supply which could supply a nominal ±120 volts, ±300 volts, and ±600 volts dc. The power supply was connected to the system analog processor so that the output could be recorded directly at the beginning of each strip chart for that flight. After completion of the calibration, the rotor and stator surfaces of each field mill, as well as the surrounding area, were cleaned with ethanol.

4.0 DATA ACQUISITION AND REDUCTION

4.1 DATA ACQUISITION

Cloud data were obtained during 25 aircraft flights (Appendix A), each about 2 hours in duration. The prime objective of each flight was to obtain data on a well-isolated anvil-type cumulonimbus cloud. Ideally, data collection during the building, maturing, and dissipating stages of the cloud was most desirable, with at least one pass made over the cloud top. Figure 5 shows the various paths flown in, around, and through a typical cloud structure.

Typically, attempts were made to fly through the cloud anvil starting at the outer edges and moving progressively in towards the core of the cloud, followed by a circuit around the outer edges of the cloud, then starting under the anvil shelf and moving progressively lower.

As the aircraft approached the cloud for a data pass, several photographs were taken. After establishing straight and level flight, recording of the electric field data was initiated. Also recorded (on the voice recorder) during the pass was time of day, aircraft altitude, air speed, heading, outside temperature and the variable omnidirectional range/distance measuring equipment (VOR/DME) reading.

4.2 DATA REDUCTION

Following each flight, the pertinent aircraft attitude information and other comments from the voice recorder were transcribed onto the cloud summary data sheets shown in figure 6. The strip charts provided continuous values of the E_x, E_y, E_z, and V_a electric field components. The values that were entered on the data sheets represented the percentage of full-scale deflection read at selected times during the pass. Typically, 6 to 20 points were used from each pass with particular attention placed on any unusual events such as fluctuations caused by observed lightning, peaks of electric fields, negative fields, and points where the recorded data crossed the zero axis.

After tabulating the raw data, the actual electric-field components were computed by applying the appropriate gain factors obtained from the preflight calibration. The resultant electric field and its angle of bearing and declination from the aircraft were then calculated and listed on the data form shown in figure 7.

5.0 DISCUSSION

During the 25 flights, data were obtained from 33 clouds at altitudes ranging up to 12 800 meters. Table I summarizes the types of clouds investigated, the maximum electric fields recorded, and the altitudes flown. To categorize the electric field data, cloud formations were defined as follows:

a. Developing anvil - a cumulus cloud rapidly building in size and altitude and characterized by a mushroom shape that is the start of the classic anvil cloud form.

b. Mature anvil - a storm cloud that has attained a sharply defined anvil top, but is no longer increasing in altitude.

TABLE I.- CLOUD SUMMARY DATA

Date	Cloud type	Number of passes	Altitude, km	Maximum field, kV/m
July 13	Dissipating anvil	10	9.5 - 12.5	47.8
July 14	Dissipating anvil - extended	4	10.1 - 12.5	49
July 15	Dissipating anvil	8	10.7 - 12.5	57
July 16	Developing anvil	20	9.5 - 12.5	94.9
July 19	Large storm system	10	6.1 - 10.7	137.5
July 20	Dissipating anvil	7	10.7 - 12.5	43.5
July 22	Mature anvil	3	12.5	15.5
	Dissipating anvil	8	8.8 - 12.5	13.2
	Dissipating anvil	4	8.8	41.1
	Mature anvil	7	8.8 - 12.5	48
July 23	Developing anvil	15	10.7	17.2
	Mature anvil	[illegible]	7.0 - 12.2	20
	Developing anvil	2	10.7	2.7
July 27	Developing anvil	12	9.5 - 12.8	53.7
July 28	Mature anvil	8	9.5 - 13.1	58.1
	Mature anvil	9	11.9 - 12.8	58
July 29	Mature anvil	9	11.3 - 13.1	65.4
	Developing anvil	5	7.3 - 13.1	42.6
	Dissipating anvil	5	11.0 - 12.8	15
	Dissipating anvil	5	11.3 - 12.8	16.2
July 30	Developing anvil	9	11.9 - 12.8	65.3
August 2	Mature anvil	16	11.3 - 12.5	96.0
August 3	Mixed cirrus and cumulus	13	8.2 - 12.8	86.9
August 5	Dissipating anvil	4	12.5	4.1
	Dissipating anvil	4	11.3 - 12.5	1.9
	Dissipating anvil	2	9.5 - 10.7	65.3
August 6	Dissipating anvil	11	9.5 - 12.2	169.5
August 9	Storm system	13	0.3 - 3.7	80.3
August 10	Mature anvil	5	11.3 - 12.8	49.3
	Storm system	9	11.3	72.2
	Dissipating anvil	7	11.3	92.0
August 11	Storm system	2	11.3 - 11.9	30.5
	Storm system	13	11.3 - 13.1	126.9
	Storm system	16	9.5 - 12.8	87.0
August 12	Storm system	17	11.3	142.0

c. Dissipating anvil - a storm cloud that has stopped increasing in size and in which the anvil is elongating and streaming. At this stage, the cloud is starting to lose its sharply defined anvil form.

d. Storm system - a large thunderstorm made up of old anvil clouds or other type clouds which seem to have combined with or collected debris from other storm clouds. These systems invariably produced severe surface rain and lightning.

The electric field data obtained from the various cloud formations are representative of the four categories of clouds, with the majority of the maximum values between 40 and 90 kV/m. No particular type of cloud appeared to produce unique electric field patterns; however, three of the four highest electric field values recorded (142 kV/m, 137.5 kV/m, and 126.9 kV/m) all came from the storm-system type formation.

The cloud electric field data and the associated vector components were plotted along the ground track of the aircraft during each pass near or through a cloud. Typical plots of these data are shown in figures 8, 9, and 10. These plots were chosen because the clouds were relatively isolated and the aircraft passes were closely grouped. The voltage gradients measured are the result of all charge pockets in the vicinity of the aircraft.

The location of the higher electric-field values within a cloud varied from cloud to cloud. Some high values were found at the top of the cloud, some at the outer third of the anvil, and some, as expected, near the core of the cloud. Figures 11 and 12 are sketches showing the location and the maximum values of electric fields in some of the clouds.

One of the largest and most severe thunderstorms encountered during the experiment was in a storm-system type formation. This storm was located between Orlando and Titusville, Florida, and was investigated on July 19, 1976, between 1500 hours and 1800 hours E.d.t. This large storm covered an area of 80 by 80 kilometers with the top estimated to be above 15 200 meters. The storm was an anvil cloud that had grown quite large and was starting to diffuse into stratocirrus clouds with embedded cells and other cloud debris. The highest electric-field value in this cloud formation was 137.5 kV/m, recorded while flying through the anvil at an altitude of 10 700 meters with the aircraft weather radar indicating that a cloud cell was penetrated. A lightning flash and precipitation were also observed. Although 10 passes were made in and around this storm system, all other electric field values were typical of those recorded in other storms during the experiment.

Data from another isolated cell and anvil, taken during 6 passes, are plotted along the aircraft ground path in figure 13. The figure shows that a relatively high voltage gradient exists in and around the anvil core center for a distance of at least 1 1/2 times the core diameter, measured from the core edge.

In the vicinity of isolated anvils, peak voltage gradients as high as 22 kV/m (fig. 14) were measured as far as 30 kilometers from the cell center, and as high as 81 kV/m (fig. 14) as far as 16 kilometers from the cell center. These values exceed the 15 kV/m maximum safe level previously established for the Apollo program launch operations. However, insufficient data were obtained to determine if unsafe gradients can exist at the outer extremity of the anvil (maximum distance from the core). The triggering levels for the Shuttle vehicle have not yet been established.

Data from 5 isolated anvils investigated during 22 passes were averaged and plotted in figure 15. The Hewlett-Packard HP67 curve fitting program was used to analyze these data. The following table shows the results of that analysis.

	Linear regression $y = a + b\,x$	Exponential $y = a\,e^{bx}$	Logarithmic $y = a + b \ln x$	Power $y = a\,x^{b}$
r^2	0.65	0.69	0.54	0.51
a	33.01	70.25	52.31	490.11
b	-0.84	-0.1	-12.98	-1.36

x = distance from core center in kilometers

y = gradient in kV/m

The exponential approximation gave the best fit ($r^2 = 0.69$) and is plotted on figure 15. Data collected from additional anvils at a later date should improve the degree of fit.

6.0 CONCLUSIONS

1. Based on Apollo criteria, voltage gradients that are high enough to allow lightning triggering exist in and around the anvils of anvil clouds. These high voltage gradients may exist as far out from the core as the down wind edge of the anvil.

2. All four types of cloud formation investigated displayed voltage gradients high enough (>15 kV/m) to allow lightning triggering, based on the criteria of 15 kV/m that was established for Saturn V operations in Apollo. The triggering value for Shuttle is yet to be established, but these data combined with future cloud data and an analysis of the Shuttle vehicle will be used to develop the Shuttle criteria.

3. Collection of more anvil cloud voltage gradient data is needed for the formulation of a better anvil cloud model. Such a model can be correlated with ground-level voltage gradient measurements taken under anvil clouds. This will allow the use of ground-level voltage-gradient measurements to predict voltage gradients in overhead anvils, and thus form the basis of the launch criteria to avoid the effects of triggered lightning during Shuttle operations.

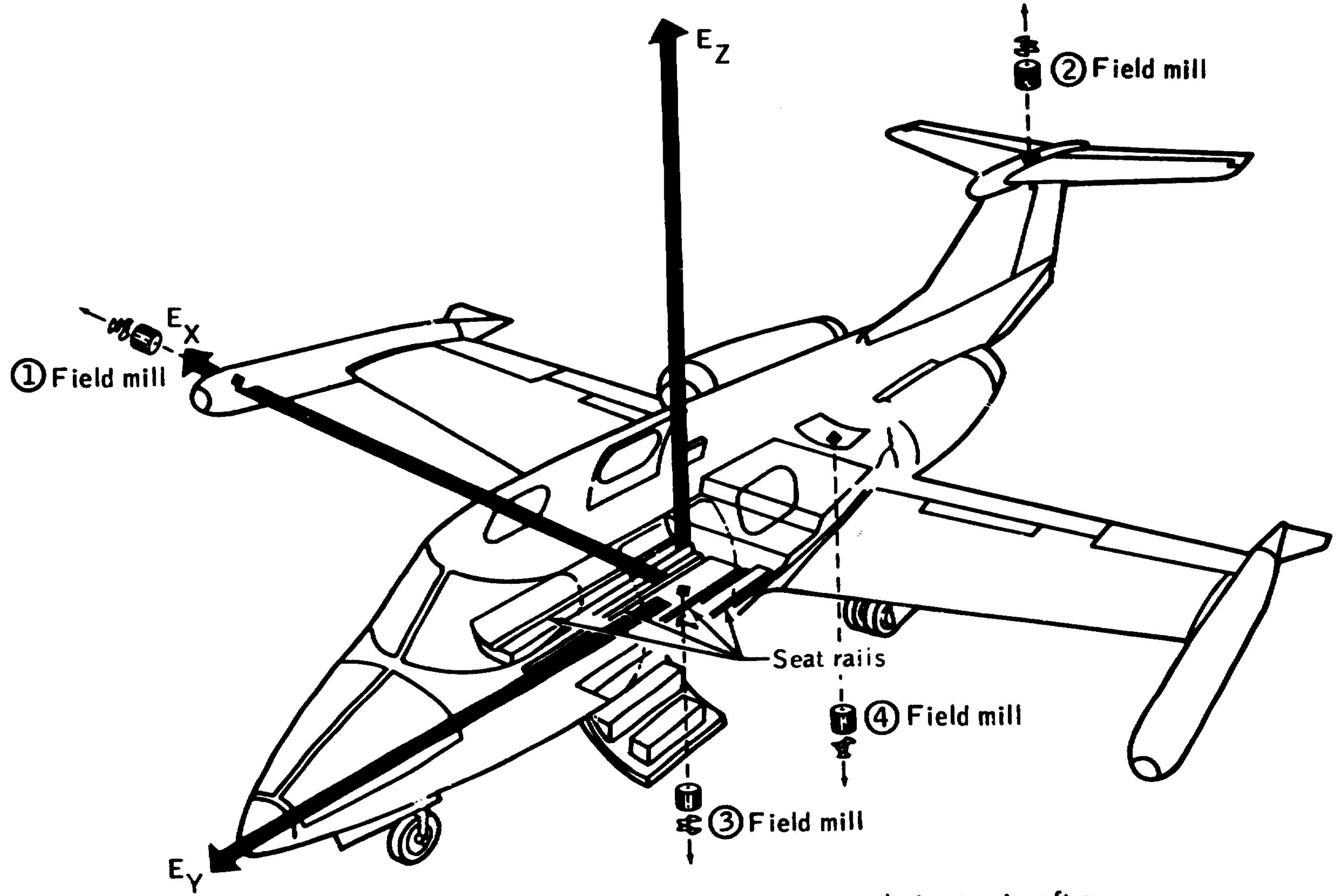


Figure 1.- Field mill locations and orientation relative to aircraft axes.

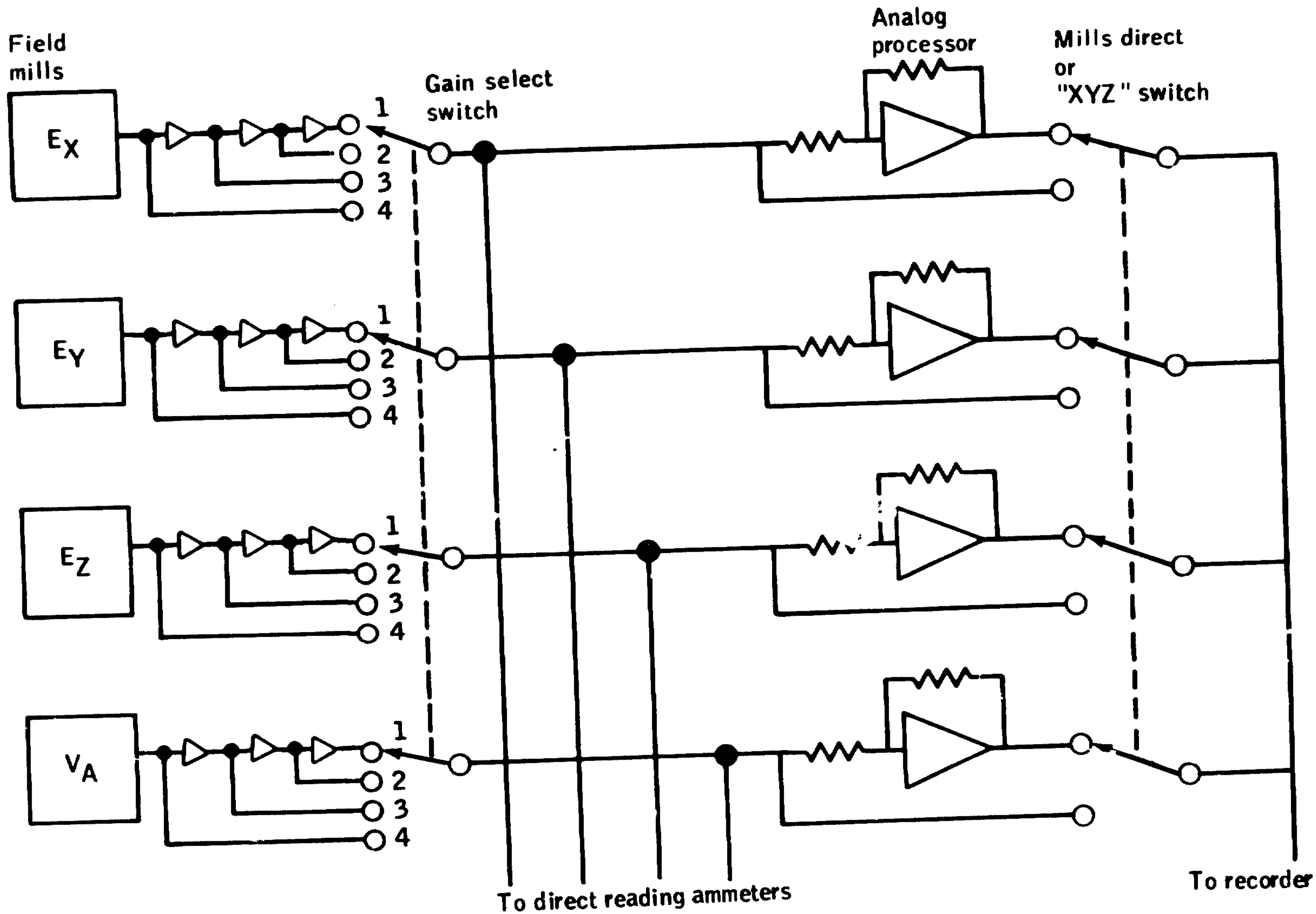


Figure 2.- Airborne electric field measurement system schematic

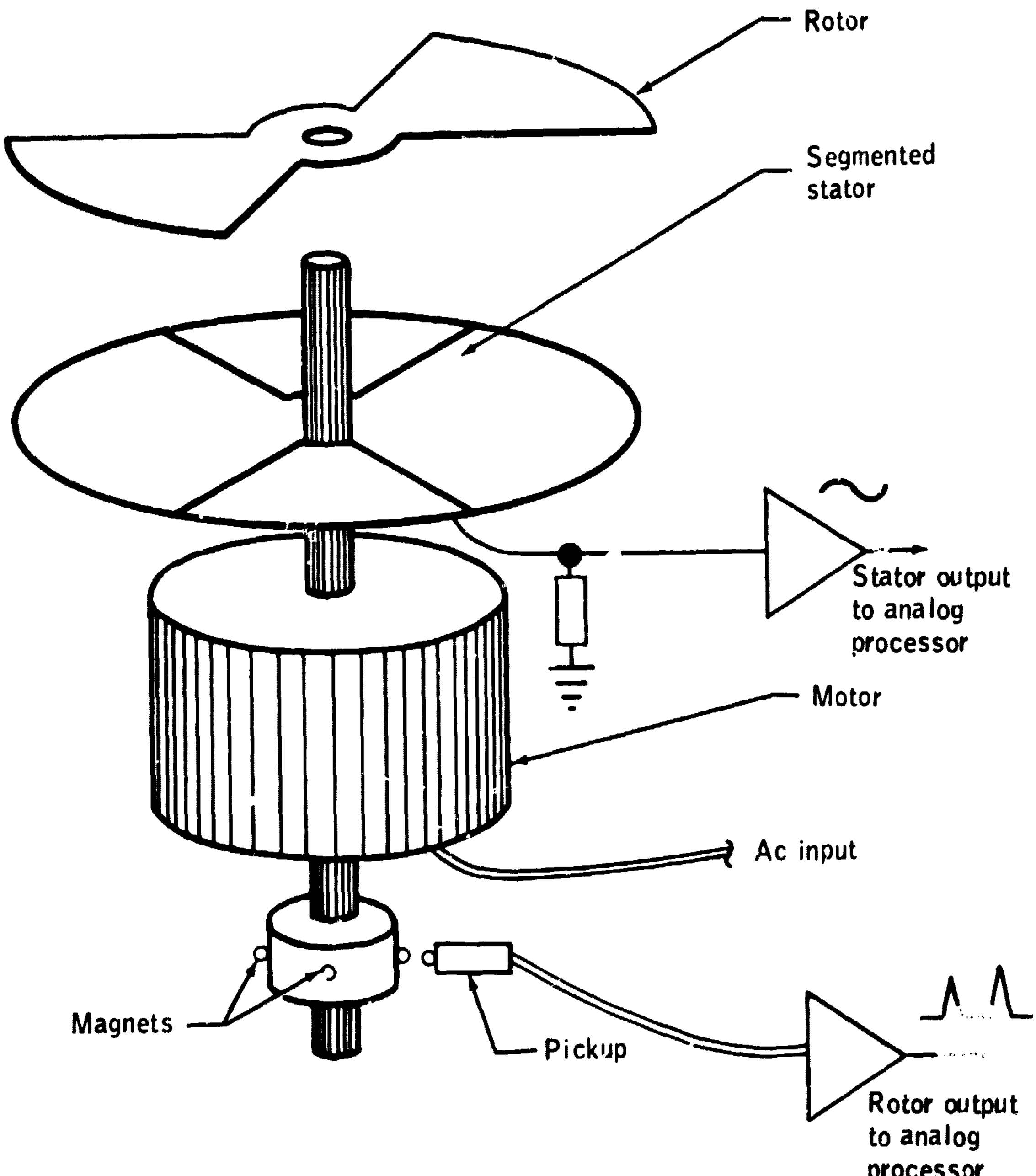


Figure 3.- Typical field mill.

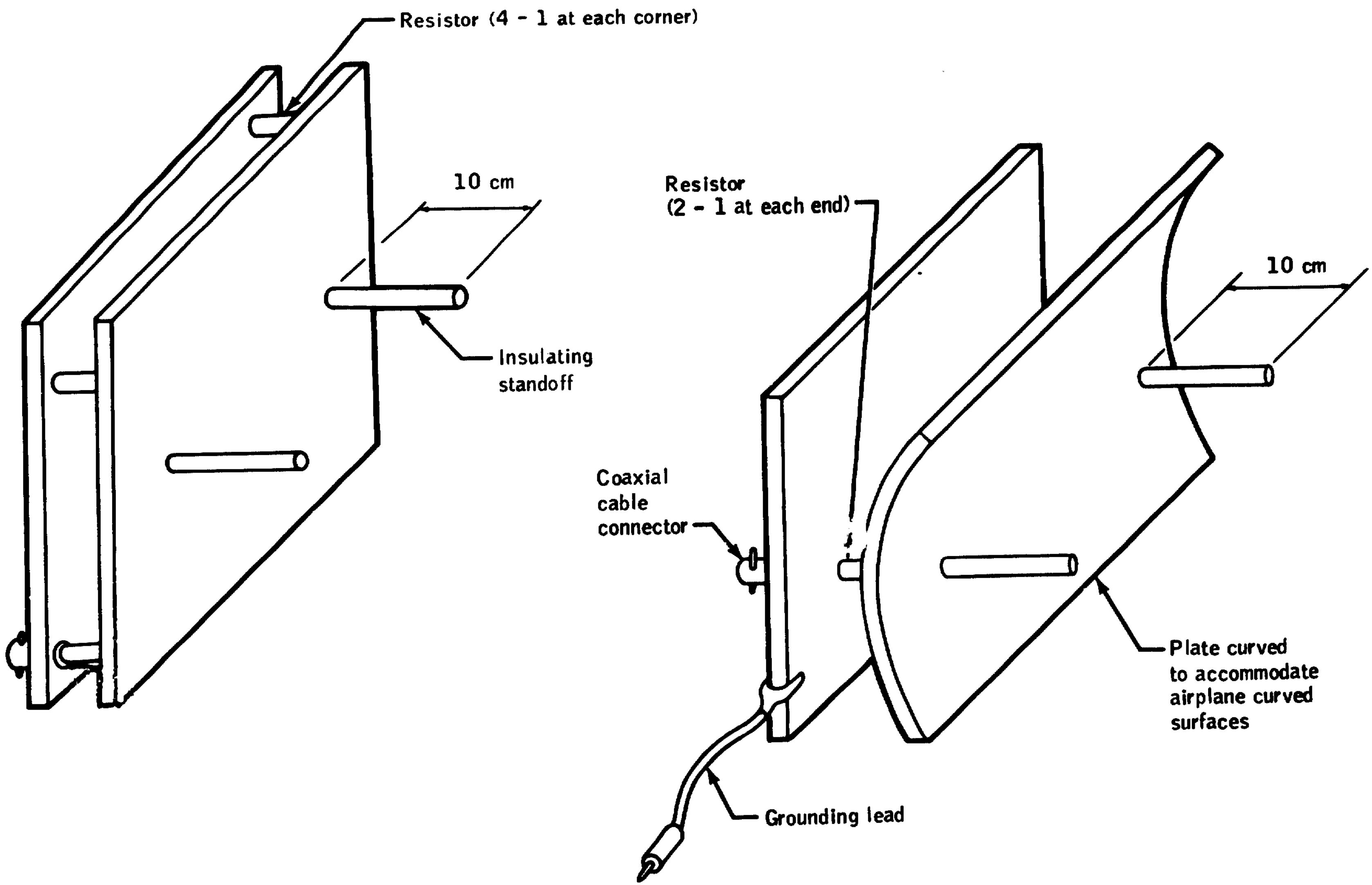


Figure 4.- Calibration plates configuration.

Figure 5.- Typical investigation of anvil.

Cloud electrification studies/Kennedy Space Center thunderstorm project data

Overall cloud summary data (Learjet)

Date	Cloud	Type	Area	Base	Top	Movement	Remarks

I. D.		Aircraft				Cloud				Max Fields			Remarks
Pass	Time in/out	Alt	Hdg	VOR/DME	Mach/T'	Temp	Top	Pos	Note	E_Z	E_X	E_Y	

KSC FORM OT–685 (7/76) (ONETIME FORM-REPRINT NOT AUTHORIZED)

Figure 6. - Raw data form.

LEAR JET PASS DATA FORM

Date ____________ Pass ____________ Cloud ____________

Ref Pt	Time	VOR/DME	V	E_Z	E_X	E_Y	Gain	$\lvert E \rvert$ KV/M	Ø	θ

KSC FORM OT–687 (8/76) (ONETIME FORM - REPRINT NOT AUTHORIZED)

Figure 7.– Computed data form.

Alt of pass	10 700m
Alt of cloud top	9 500m
Cloud type	Developing anvil

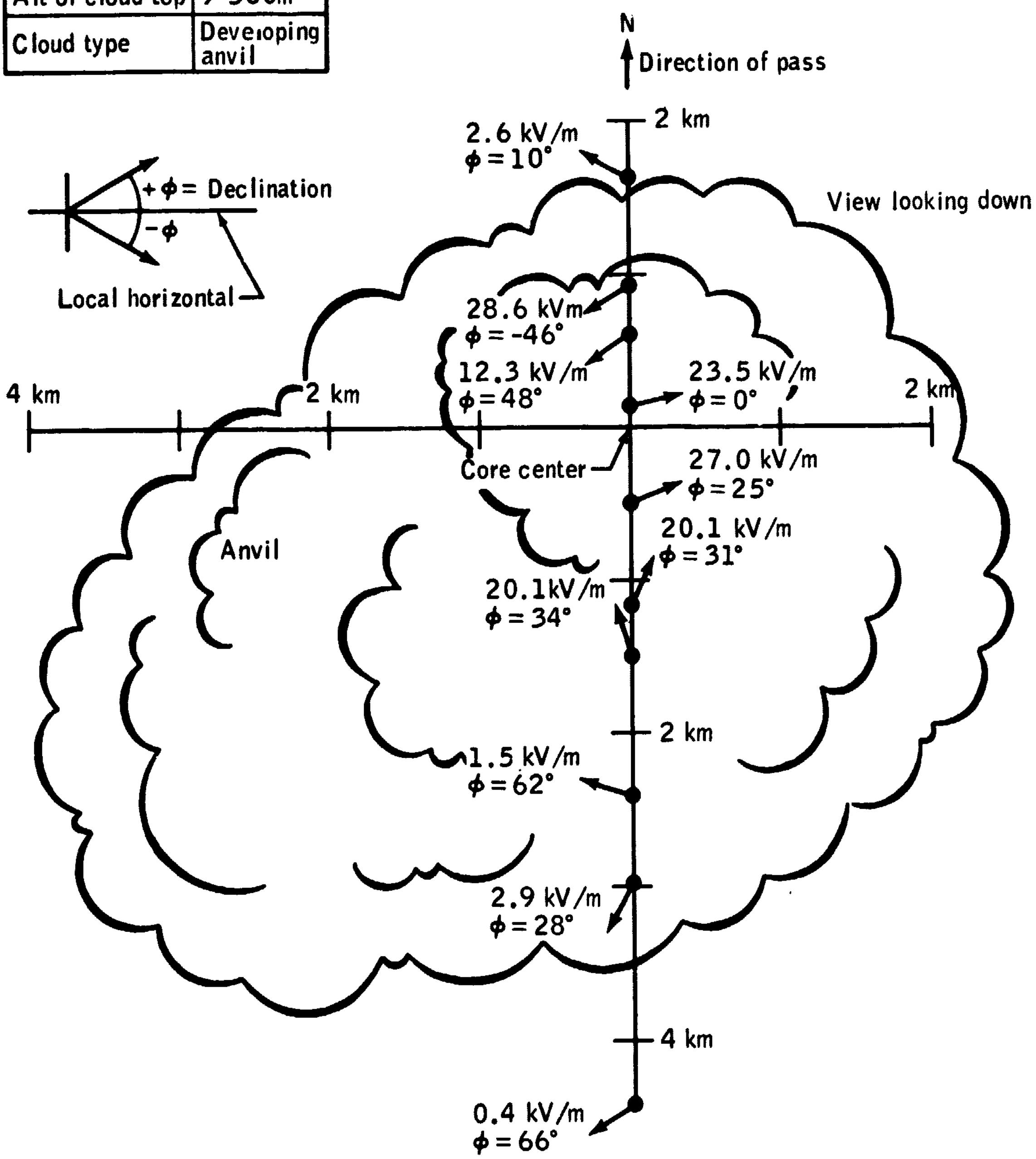


Figure 8.- Electrical field strengths and vectors sensed during pass 7 on July 27, 1976.

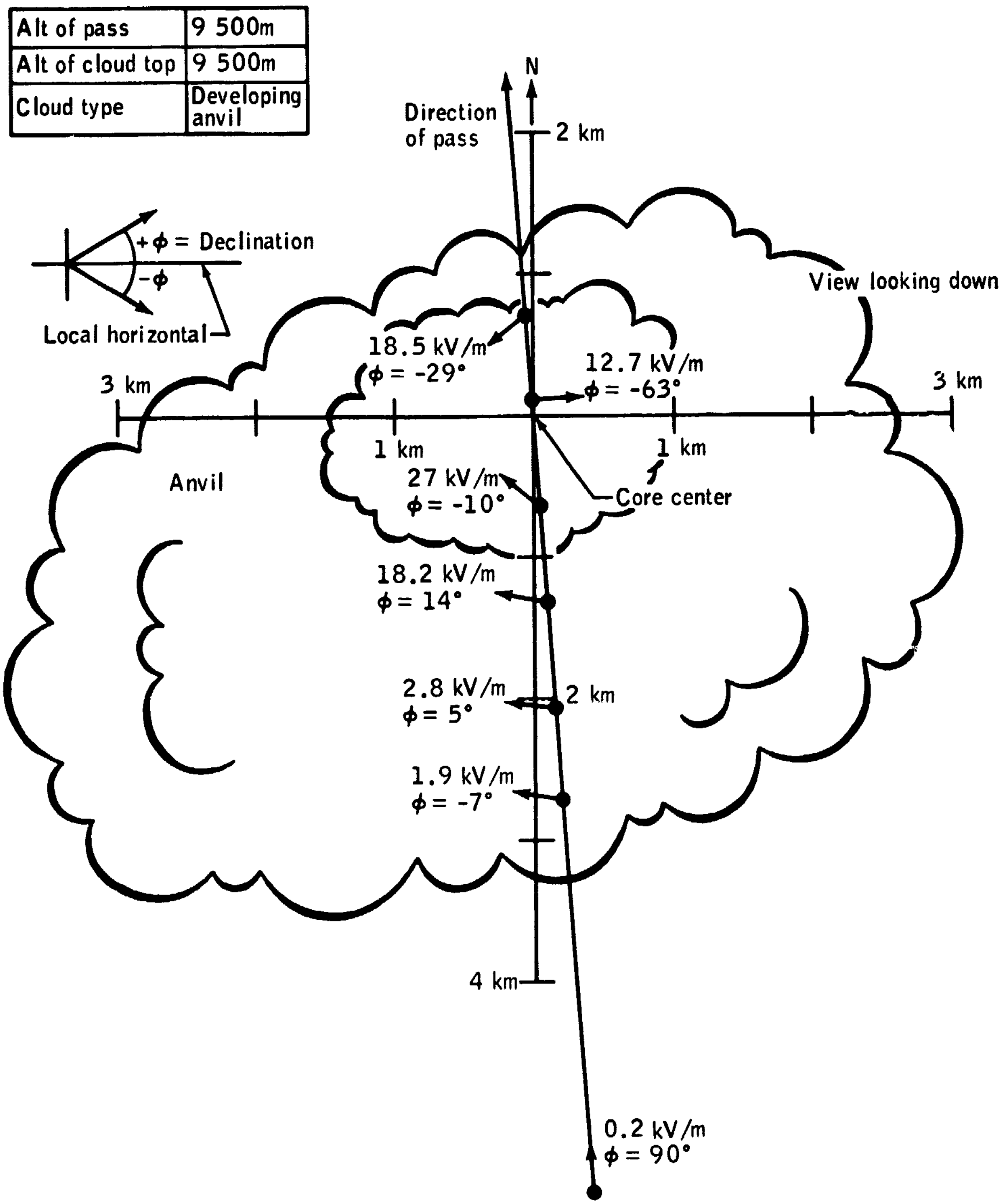


Figure 9.- Electrical field strengths and vectors sensed during pass 13 on July 27, 1976.

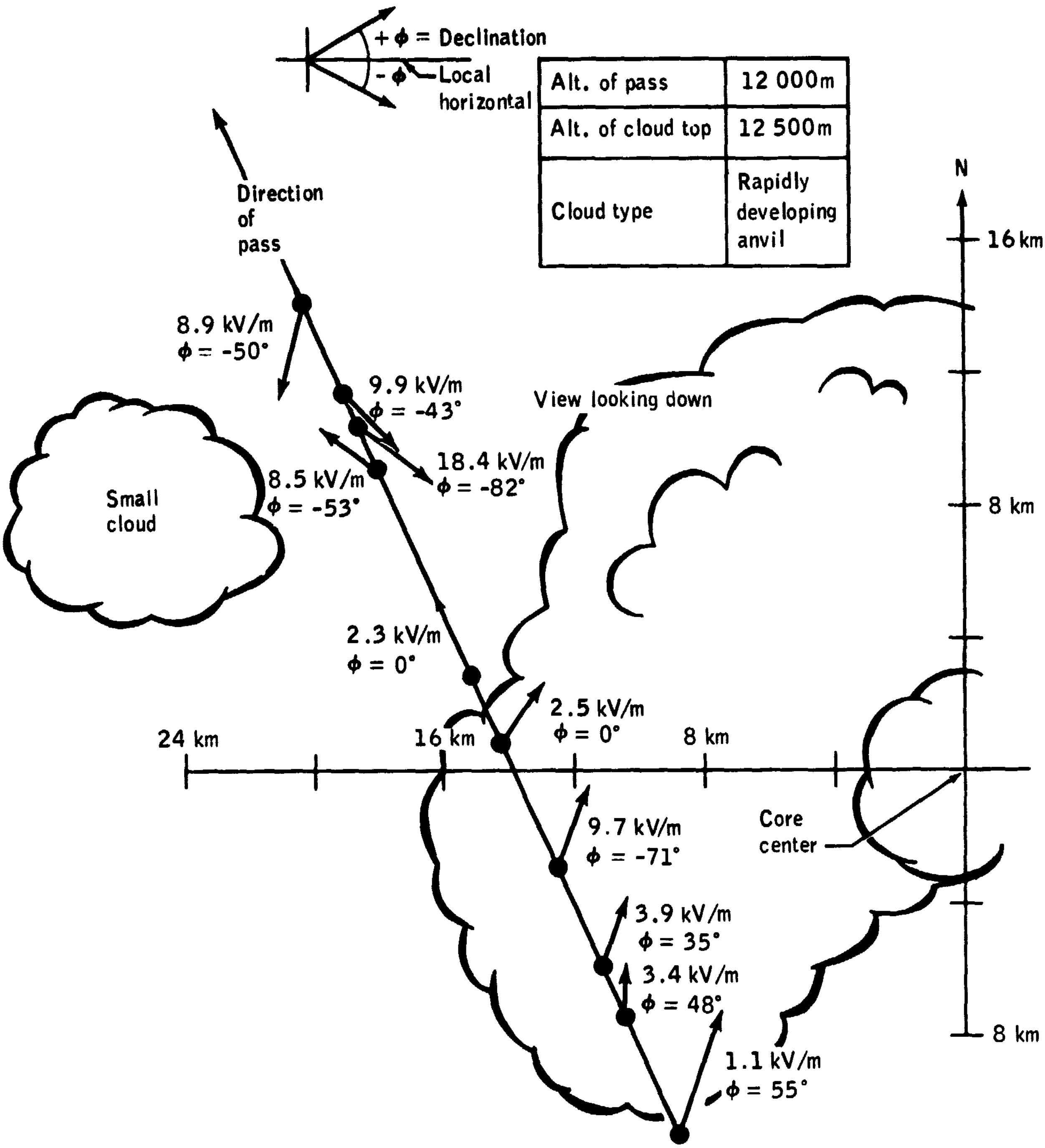
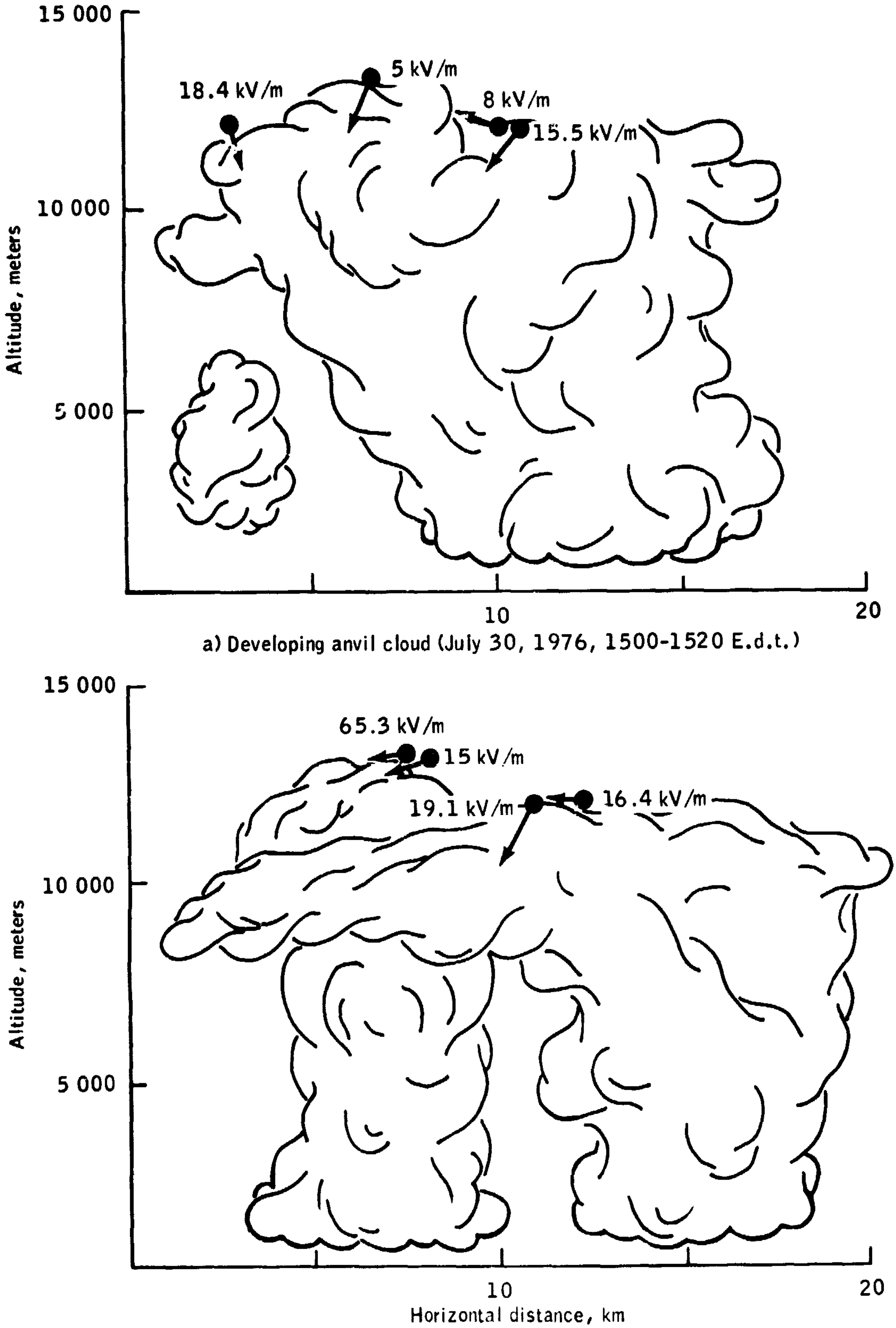


Figure 10.- Electrical field strengths and vectors sensed during pass 1 on July 30, 1976.



a) Developing anvil cloud (July 30, 1976, 1500-1520 E.d.t.)

b) Further development of anvil cloud (July 30, 1976, 1540 - 1546 E.d.t.)

Figure 11.- Maximum value of electrical field at top of cloud.

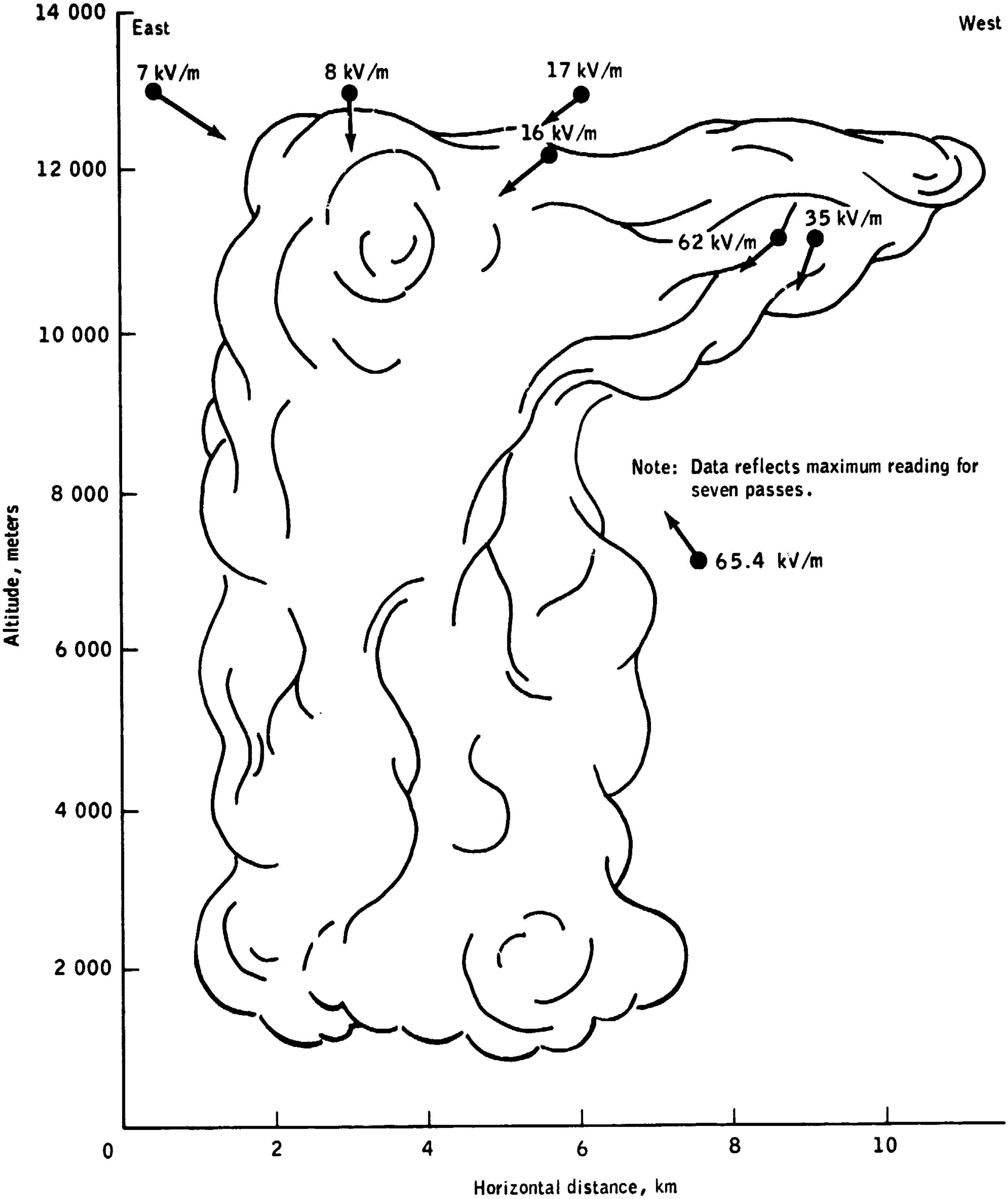
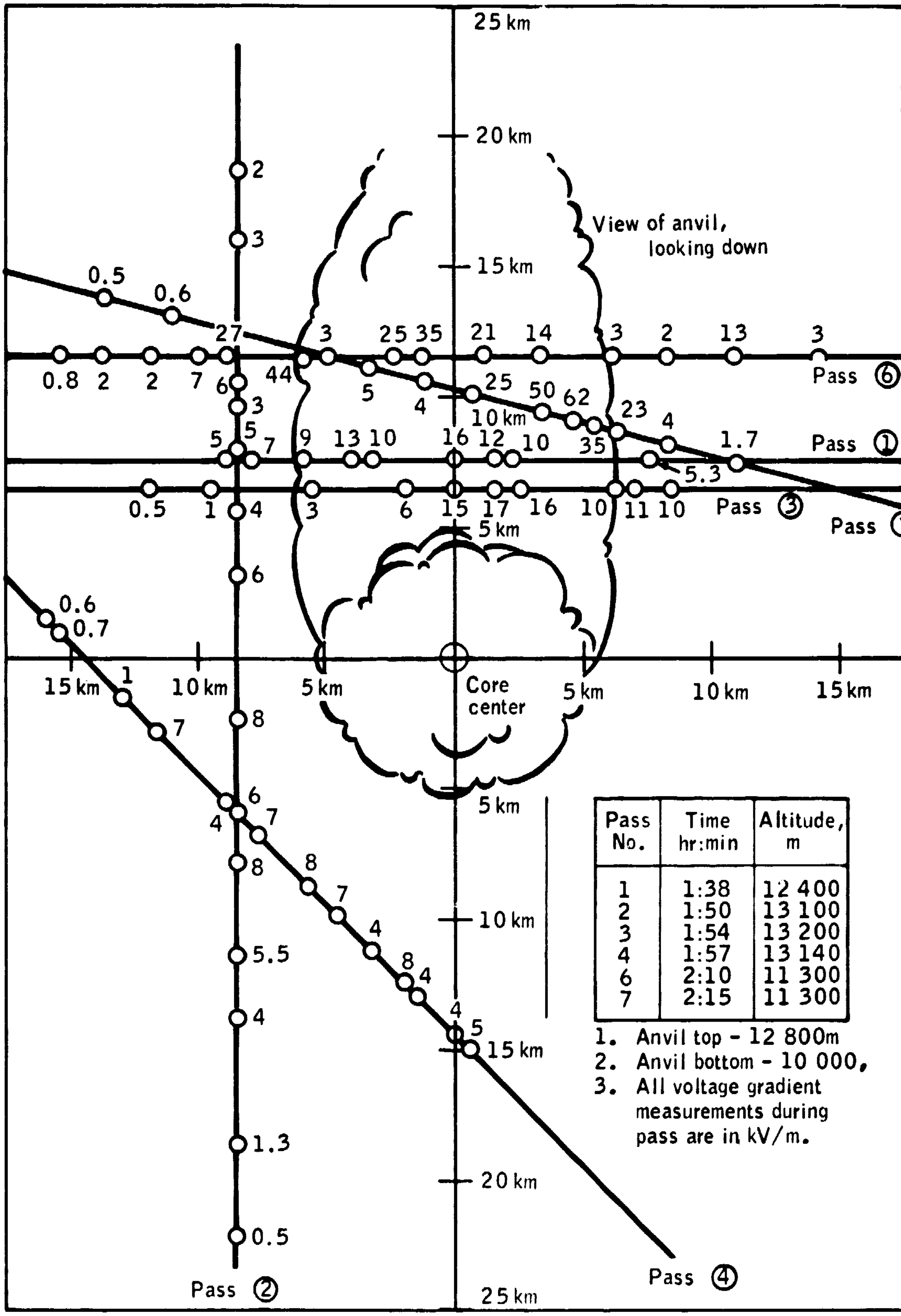


Figure 12.- Maximum value of electrical field at outer third of anvil (July 29, 1976).



Pass No.	Time hr:min	Altitude, m
1	1:38	12 400
2	1:50	13 100
3	1:54	13 200
4	1:57	13 140
6	2:10	11 300
7	2:15	11 300

1. Anvil top - 12 800m
2. Anvil bottom - 10 000,
3. All voltage gradient measurements during pass are in kV/m.

Figure 13.- Voltage gradient data from isolated anvil cloud on July 29, 1976.

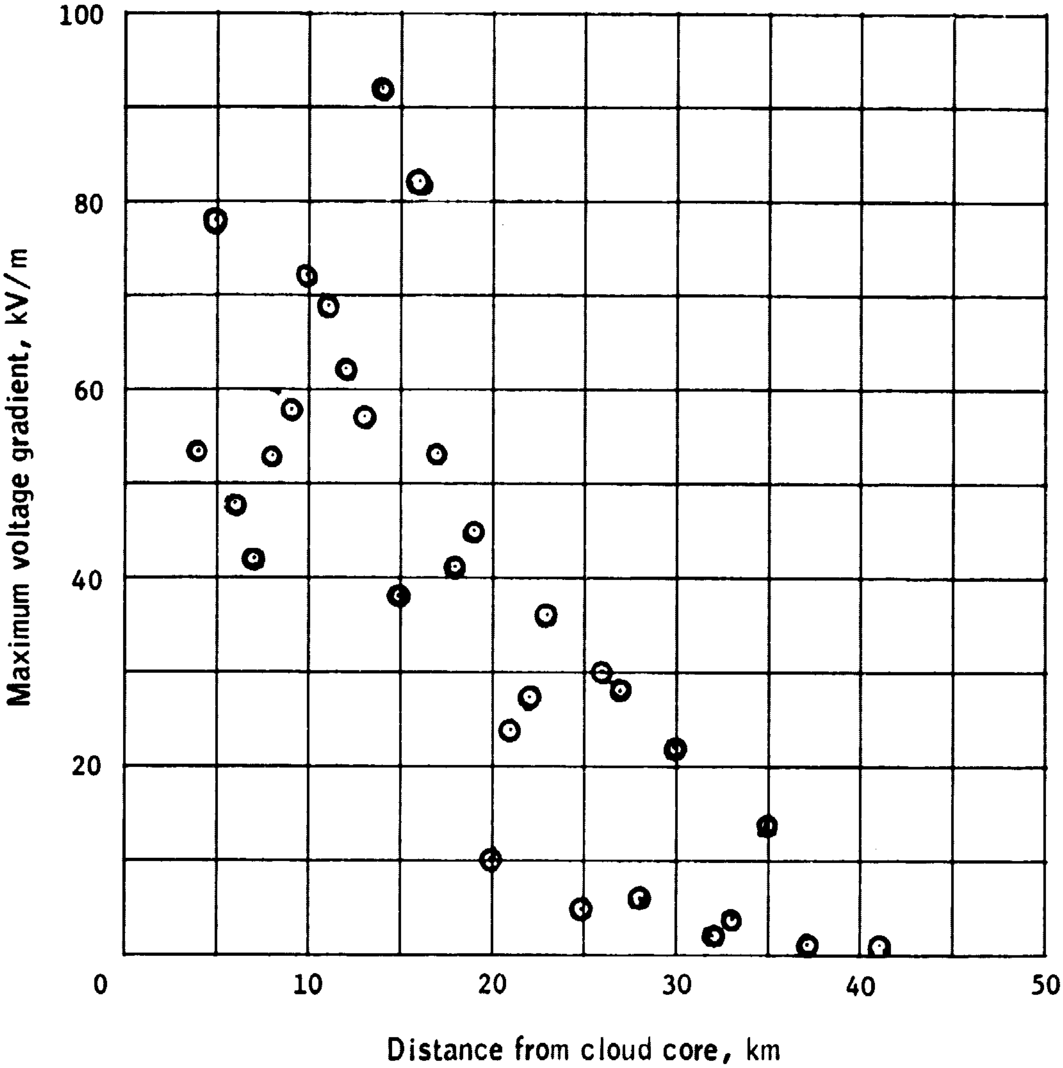


Figure 14.- Maximum voltage gradients measured in isolated anvil clouds.

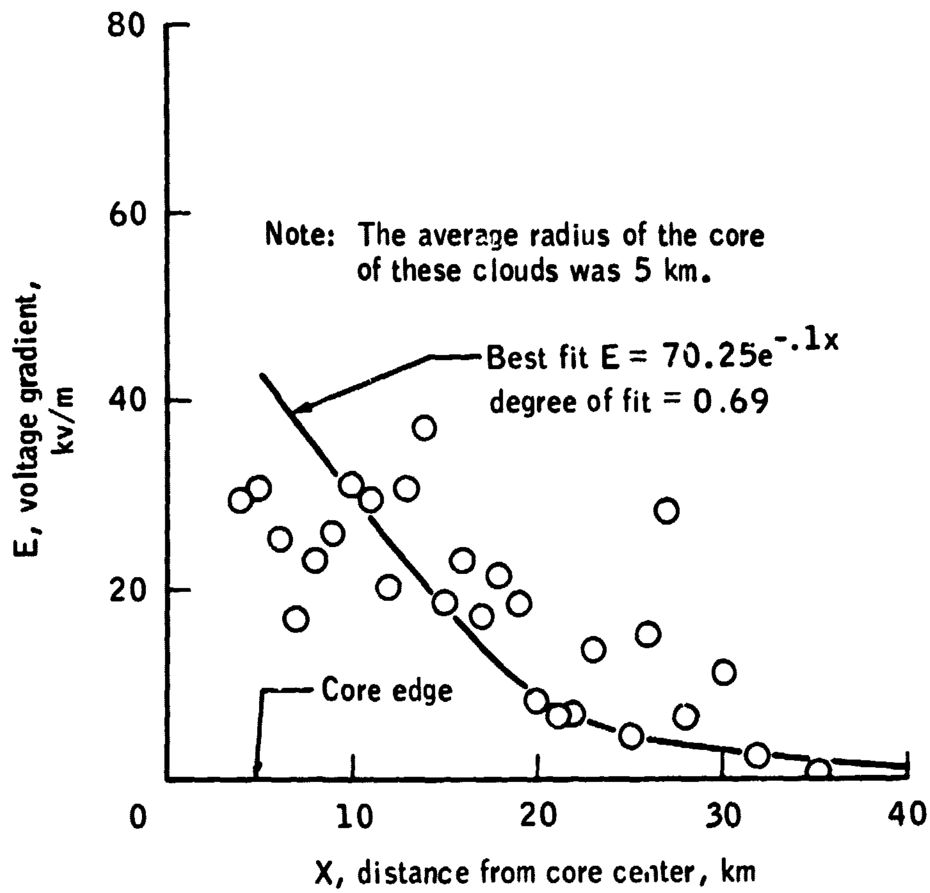


Figure 15.- Averaged voltage gradient data from 22 passes around 5 cloud anvils.

APPENDIX A - FLIGHT HISTORY

Date	Time, E.d.t.	Aircraft altitude, km	Remarks
July 13, 1976	1500-1730	10.7-12.2	Investigated dissipating anvil near Vero Beach, Florida
July 14, 1976	1500-1700	9.1-12.2	Investigated anvil near Ormand Beach, Florida
July 15, 1976	1500-1730	10.7-12.2	Investigated dissipating anvil near Vero Beach, Florida
July 16, 1976	1600-1800	10.7-12.5	Investigated anvil near Orlando, Florida
July 19, 1976	1600-1800	10.7-12.5	Investigated storm system (50 x 50 mi.) over St. Johns River, west of Titusville, Florida
July 20, 1976	1600-1800	10.7-12.5	Investigated anvil near Miami, Florida
July 22, 1976	1300-1500	10.7-12.5	Investigated isolated anvil near Miami, Florida
	1700-1830	10.7-12.5	Investigated isolated anvil near Miami, Florida
July 23, 1976	1300-1500	10.7-12.5	Investigated storms near Vero Beach, Florida
	1600-1800	10.7-12.5	Investigated anvil west of Orlando Florida
July 27, 1976	1500-1700	8.2-12.5	Investigated isolated anvil west of Daytona Beach, Florida
July 28, 1976	1300-1500	10.7-12.5	Investigated anvil near Lake Okeechobee, Florida
	1600-1800	10.7-12.5	Investigated anvil near Lake Okeechobee (aircraft engine flame-out restarted)
July 29, 1976	1315-1500	8.2-12.5	Investigated mature isolated anvil west of Palm Beach, Florida
	1600-1800	8.2-12.5	Investigated mature anvil and other clouds near Palm Beach, Florida

APPENDIX A - FLIGHT HISTORY - Concluded

Date	Time, E.d.t.	Aircraft altitude, km	Remarks
July 30, 1976	1430-1630	8.2-12.5	Investigated isolated anvil between Daytona Beach and Titusville, Florida
August 2, 1976	1415-1630	8.2-12.5	Investigated mature anvil near Lake Okeechobee, Florida
August 3, 1976	1345-1530	10.7-12.5	Investigated large cloud system - cirrus with imbedded cumulus-south of Sarasota, Florida
August 5, 1976	1515-1730	10.7-12.5	Investigated series of clouds from Titusville to Daytona Beach, Florida
August 6, 1976	1530-1730	9.[illegible]-12.5	Investigated clouds south of Patrick AFB, Florida
August 9, 1976	1400-1600	5.5-12.5	Investigated large storm system near Lake Okeechobee, Florida
August 10, 1976	1345-1600	9.5-12.5	Investigated storm systems from Palm Beach, Florida, to Titusville, Florida. (Aircraft struck by lightning - minor damage)
August 11, 1976	1300-1500	9.5-12.5	Investigated cloud system near Lake Okeechobee, Florida
	1400-1600	9.5-12.5	Investigated cloud system between Lake Okeechobee, Florida, and Orlando, Florida
August 12, 1976	1300-1500	9.5-12.5	Investigated cloud system near Ft. Myers, Florida

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